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Coil system and voltage rectifiers for communication and inductive powering of devices inside rotating tyre of a vehicle

The invention relates to communication and power feeding devices for tyres of vehicles
according to the preamble of claim 1.

The invention relates also to communication methods for tyres of vehicles.

The invention also relates to a tyres.

According to conventional techniques, there have been pressure sensors in tires powered by
batteries. However, battery technology is not reliable and the batteries may run out of energy
just at the moment the sensor is needed the most.

Also such technologies are used in the prior art where normal RF-transponders are positioned
in the tires. This technology is however not very reliable in rough vehicle conditions.

It is an object of the present invention to overcome the above-described problems of the
prior-art techniques and to provide an entirely novel device for feeding power to an
electronic device in a tyre.

The goal of the invention is achieved by virtue of a coil arrangement in a tyre and a
corresponding coil arrangement in a vehicle close to the tyre.

More specifically, the device according to the invention is characterized by what is stated in
the characterizing part of claim 1.

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Furthermore, the method according to the invention for feeding power to an electronic device in a tyre is characterized by what is stated in the characterizing part of claim 6.

5   The invention offers significant benefits over conventional techniques. The power feeding is continuous and enough power is available always, especially in the driving conditions where the information e.g., from tire pressure is needed the most.

The system is simple and the production costs are low. Further, the invention can be used with any kinds of electrical loads.

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In the following, the invention will be examined with the help of exemplifying embodiments by making reference to the appended drawing, wherein

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Fig. 1 shows a scheme of inductive power transmission according to the invention.

Fig 2 shows the schematic diagram of the AB-class power amplifier according to the invention, where the feed coil L1 is tuned with a capacitor C2.

Fig. 3a shows as a perspective view the four receiving coils and two rectifiers in the inner
20   liner of the tire according to the invention.

Fig 3b shows figure 3a as a top view.

Fig. 4 shows circuit of the voltage rectifiers according to the invention, four tuned receiving
25   coils connected to load resistor R and the device for communication consisting of transistor T1 and resistor R2.

Fig 5 is a graph illustrating the power in the R = 500Ω load resistor versus frequency at the distance of 11cm. (Q $\approx$31)

Figure 6 is a graph illustrating the power in the 500Ω resistor versus frequency at the distance of 2 cm. (*Q* ≈22).

Figure 7 is a graph illustrating the power in the 500Ω resistor versus frequency at the distance of 11cm. An aluminium block was installed 5cm behind the feed coil.(*Q* ≈30).

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Figure 8 is a graph illustrating the power in the 500Ω resistor versus frequency at the distance of 11cm. An iron block was installed 5cm behind the feed coil. (*Q* ≈28).

Figure 9 is a graph illustrating the power in the 500Ω resistor versus frequency at the

10   distance of 17cm. An empty bucket was installed between the coil and the test tire. (*Q* ≈33).

Figure 10 is a graph illustrating the power in the 500Ω resistor versus frequency at the distance of 17cm. An Bucket full of water was installed between the coil and the test tire. (*Q* ≈33).

15   Figure 11 is a graph illustrating the power in the 500Ω resistor versus turn angle of the wheel at the distance of 11 cm.

Figure 12 shows an arrangement where the transmitted power versus frequency is being measured. The coil is at a distance of 11cm from the surface of the tire.

Figure 13 shows an arrangement where a test setup is installed to measure the effect of an

20   aluminium block to the transmitted power.

Figure 14 shows s test setup is installed to measure the effect of a bucket full of water to the inducted power.

Figure 15 shows a feed coil and amplifier according to the invention.

Figure 16 shows receive coils in tyre and feed coil in the wing according to the invention.

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Figure 17 shows an alternative position of the feed coil according to the invention. This position, shown for front wheel, ensures that the distance between feed coil and receiver coil does not vary.

Figure 18 shows figure 4 configured in a new way.

5   **1.   Basics**

To transmit power wirelessly over a short distance one feasible solution is to use alternating magnetic field. Relatively high energy density of the magnetic field allowed at certain RF frequencies makes it possible substantial power transmission over short distances. Voltage induced into a coil by a changing magnetic field is determined by the Faraday's law

10    $$U = -\frac{\partial}{\partial t}\Phi,$$ [1]

where Φ is a magnetic flux through an area A according to formula

$$\Phi = \int_A \vec{B} \cdot d\vec{S}$$ [2]

and where $\vec{B} = \mu\vec{H}$ is the density of a magnetic flux. On the other hand, a current i in a loop c generates a magnetic field $\vec{H}$ at point $\vec{r}$ according to Biot-Savart's law

15    $$\vec{H}(\vec{r}) = \frac{i}{4\pi}\oint_c \frac{d\vec{c}' \times \vec{u}_D}{r^2},$$ [3]

where r is distance between the point of consideration and current element $d\vec{c}'$. We can make two important notes from the formulas [1] and [2]. First, if we have high current we have large magnetic field and, thus, high induced voltage. Second, if we differentiate sine-form current with an angular frequency $\omega = 2\pi f$

20    $$\frac{\partial i}{\partial t} = \frac{\partial \hat{i}\sin(\omega t)}{\partial t} = \hat{i} \cdot \omega\cos(\omega t),$$ [4]

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we notice that the higher the frequency of the current, the higher the induced voltage. Therefore we should maximize both the frequency and the current in the feed coil.

2.   **Frequency Bands and Maximum Transmittable power**

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The frequency bands allocated to inductive applications in most European countries are listed in Table1 (ERC Recommendation 70-03, December 2002). Considering the power transmission from the vehicle chassis into the tire, the most interesting frequencies are 6.78 MHz, 13.56 MHz, and 27 MHz.

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Frequency band [MHz]	Maximum magnetic field @10m [dBμA/m]	Used bandwidth [kHz]
6.765 - 6.795	42	30
7.400 - 8.800	9	1400
13.553 - 13.567	42	14
26.825 - 27.260	42	326

Table1. Frequency bands allocated to inductive applications in Europe. The middle column gives the maximum magnetic field allowed at the distance of 10 m from the device. 42 dBμA/m = 125.9 μA/m and 9 dBμA/m = 2.82 μA/m.

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The authorities limit the maximum magnetic field produced by the device at the distance of 10 m. Using this limit we can estimate the maximum current in the feed coil with a given dimensions. The magnetic field is (Stratton p. 437)

$$H_\theta = \frac{1}{4\pi}\left(\frac{1}{r^3} - \frac{jk}{r^2} - \frac{k^2}{r}\right)\sin\theta \; m \; e^{-j\omega t},$$

[5]

where k is

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c},$$

[6]

m is the dipole moment of the coil and r is the distance from the coil. The parameter $\lambda = c/f$ is the wavelength, c is the speed of light and f is the frequency. Dipole moment can be approximated by

$$m = N\,i\,A,$$

[7]

where N is the number of turns, i is the current, and A is the area of the coil.

When estimating the maximum magnetic field produced by a coil at a distance of $r = 10$ m, all the terms of equation 5 must be considered. In fact, the last term that represents radiation is dominating at all frequencies given in Table 1. From the equations above we get for the maximum overall current in the coil

$$i = \frac{4\pi}{\dfrac{NA}{r}\sqrt{\left(\left(\dfrac{1}{r^2} - k^2\right)^2 + \left(\dfrac{k}{r}\right)^2\right)}} H_{max}.$$

[8]

Consider Fig. 1. A current i flows in the feed coil L_f that is inductively coupled to the receiving coil L_c by mutual inductance M. When the receiving coil is tuned to a resonance by

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a capacitor, the power given to the resistor R, which represents the losses of the sensor and communication electronics circuit seen at the input of voltage rectifier, is given by

$$P = \frac{\omega^2 M^2}{R} |i|^2.$$ [9]

Combining Eqs. 8 and 9 we obtain the maximum power that is limited by the regulations:

$$P = \frac{\omega^2 M^2}{R} \frac{16\pi^2}{\dfrac{N^2 A^2}{r^2}\left[\left(\dfrac{1}{r^2} - k^2\right)^2 + \left(\dfrac{k}{r}\right)^2\right]} H_{max}^2.$$ [10]

3. Experimental

3.1 Feed coil

The feed coil's dimensions (A = 310mm x 133 mm) were designed to cover sufficient area of the surface of the tire when placed on the wing of the vehicle. The coil was made of 3.2 mm hollow copper pipe to ensure low resistance and low dissipation in the coil. The number of turns of the coil is N = 2.

Table 2 gives the maximum allowed rms current in the coil calculated by using Eq. 8 and also the figure proportional to the transmitted power by using Eq. 10. From this last figure one can conclude that the 6.8 MHz frequency range would be optimal, if the highest allowed current can be realized.

Frequency band [MHz]	Maximum allowed current i[A], N = 2	Maximum RMS volt [V] @i_{max}	Maximum achievable power [W] in tire (approximative)
6.765 - 6.795	11.23	1010	10

7.400 - 8.800	0.17	19	0.003
13.553 - 13.567	2.58	490	2
26.825 - 27.260	0.62	411	0.5

Table 2. The maximum current allowed in the planar feed coil used in this study. The last column gives a figure proportional to the power transmitted for the maximum allowed current in the feed coil (Eq 10).

The impedance of the feed coil was measured at four frequencies given in table 3. The impedances are measured when the coil is in air and there is no external loading. Table 3 also lists the Q values.

Frequency (MHz)	Impedance (Ohm)	Q value
6.78	1.0 + j90.1	90
13.56	2.1 + j189	90
27	59 + j663	11
36.3 (self resonance)	3210	

Table 3. The impedance and Q value of the feed coil at four frequencies.

From Table 2 one can conclude that the highest allowed current is extremely difficult to realize in practice. This would lead to too high a voltage in the feed coil. The feed coil is tuned with a series capacitor. The capacitor must be able to withstand the same voltage as the coil.

The sensitivity of the coil impedance to the presence of the tire was studied at 6.78 MHz. When the coil was placed in touch to the tread the impedance chanced to $Z = 3.6 + j93.3 \ \Omega$. This means that in order to keep the coil tuned, the capacitor should vary from 261 pF to 252

pF. The raise in resistance (1 Ω vs 3.6 Ω) is not critical. It means that the conductive rubber of the tire gives additional loading and the coil warms up the tire. The relatively small change in the capacitance, 9 pF, when the coil is brought in touch with the tire indicates that real-time tuning of the coil is not necessary. The coil must be tuned only during the initialization sequence at the vehicle start.

3.2   Power amplifier

Fig 2. The schematic diagram of the AB-class power amplifier. The feed coil L1 is tuned with a capacitor C2.

For testing the inductive supply an rf power amplifier was designed and constructed. It is intended to amplify a sinusoidal signal from an oscillator. In the tests a signal generator was used instead of an oscillator. A compromise was made between the power efficiency and the level of distortion. Therefore we ended up using an AB class push-pull output stage whose schematic diagram is seen in figure 2.

The values of used components can be seen in Table 4. Capacitors C1 and C3 have large values in order to show a low impedance at the frequency of 6.78MHz.

Component	Value
R1	875Ω
R2	619Ω
R3	14.1Ω
R4	22.7Ω
R5	0.25Ω
R6	0.25Ω
C1,C3	1μF
C2	259pF

Table 4. Component values of the circuit on figure 2.

3.3 Components

The power supply works at relatively high frequency and it must provide a high current into the series tuned feed coil. These requirements are demanding to the quality of the transistors used in the circuit. The transistors Q2 and Q3 should have high level of maximum collector current (more than 2 A_{rms}), withstand high level of power dissipation (at least 10 W) and be fast (f_t around 200 MHz). Because of the low level of the load impedance, as high a current gain, $h_{f,e}$, as possible is recommended as well. Semelab's transistors BUP40 (PNP) and BUP41 (NPN) were decided to be used. These transistors satisfy all the other specifications, but the speed of the transistors (f_t = 120 MHz) was barely tolerable. Using these transistors at higher frequency bands than 6.78MHz is not advisable. Using these transistors in a Darlington connection is not a functional solution, either. Also it is worth noting that transistors with a higher value of f_t would suffer lower levels of distortion and signal impurity.

Transistor Q1 should have, also, high f_t and h_{fe}, but high values of power dissipation and collector current are not required.

3.4 Circuit

When the circuit was designed, attention was paid to the fact that the power source of the amplifier is a 12 V battery; no two-sided voltage source is available. Therefore the input signal was biased to 6 V. This is done with transistor Q1 in figure 2. Q1 acts as a voltage follower lowering at the same time the required current level of the input signal.

Transistors Q2 and Q3 operate in a push-pull fashion as emitter followers.

Diodes D1 and D2 (1N4148) compensate the voltage drop over np-junction between the base and the emitter of the transistors Q2 and Q3. Although in this case the voltage drop over

diode is greater than the voltage drop over base and emitter of the BUP4x transistors. This is
compensated by coupling several diodes parallel. In this way the amount of current passing
through each diode is low enough that, according to the *i-v* graph of a diode, the voltage is
lower over the junction.

5   Warming-up and thermal instability are problems faced when working with power
amplifiers. Small resistances R5 and R6 at the emitters of transistors Q2 and Q3 are there to
prevent thermal runaway.

High input impedance is always recommended in an amplifier circuit reducing the level of
10   current demanded from the signal source. When dealing with high currents the impedance
levels are set to be low. Problem arises when we have low biasing resistances, as it is in this
case. Because these resistors are parallel with the load, they affect greatly to the amount of
input impedance. In this circuit a technique called "bootstrapping" is used. Large capacitor
C3 ensures that ac voltage between the nodes of resistor R3 remains fairly the same, while at
15   same time dc biasing is working as it should. Thus the ac current through R3 is almost zero
and therefore $r_3 = u/i \approx \infty$. Now only the load resistance (and the current gain) affects the
amount of input resistance. Alas, the poor frequency characteristic of BUP4x transistors
lowers current gain as frequency rises, lowering the input impedance at the same time.

20   To prevent unwanted oscillation a large capacitor is placed across the ground and the voltage
source. This component is not shown in the schematic in figure 2.

3.5   *Receiver coils in tire*

At first the optimal position of the coils in the tire were tested. A configuration where the coil
runs circumferentially around the tire's inner surface turned out to be unsuitable for several
25   reasons. First, the inductive voltage was too low due the relatively high impedance of the
coil; although, some improvement would have been made if more loops had been coupled
parallel in the coil. Nevertheless this would have brought the lowest resonance frequency of
the coil too near the used transmission frequency. Second, the mutual inductance of a feed
coil and a circumferential receiver coil is low. Third, when the AC magnetic field penetrates

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the side wall of the tire, eddy currents are generated in the rim. These currents tend to lower the coupling between feed and receiver coil even further.

Receiver coil and feed coil configuration shown in Figs. 3 and 12 is a better solution, in which the magnetic of the feed coil goes through the belt of the tire. There are four separate receiver coils, which have individual voltage doubler rectifiers. In this way the coil system works below self resonant frequency of the coil. If there were only one coil, its self resonant frequency would be below 6 MHz. The self resonant frequency of each one-turn coil is also increased by making the winding from three parallel wires.

There are two alternatives to place the feed coil: vertically on the lower edge of the wing or on a separate support attached on the suspension of the wheel. This way the transmitted magnetic field remains fairly the same regardless of the vertical position of the wheel in different loading conditions.

Length	630 mm
Width	160 mm
Distance between parallel loops	4-8 mm
The length of overlapping area of neighbouring coils	110 mm

Table 3. The dimensions of the coils inside the tire (average values).

These reasons had led to an alternative approach in which four coils were installed on the inner surface of the test tire to enable optimal inductive power transmission. The results in this report are on this configuration only. The receiver coil configuration in the tire is shown in figure 3. Each coil is made of three parallel loops to lower the impedance of the coil. The wire in the loops is standard steel cord, Bekaert diameter 0.35 mm, used in the tire belt. The wires were attached on the inner liner whose surface was covered with non-conducting rubber layer (silicone). The coils covered the whole planar area of the tire's inner surface and

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where installed partly overlapping to ensure that induced voltage would not drop too low
when the feed coil is between the two receiving coils, see figure 3.

3.6 Electronics

The induced voltage was rectified with a voltage doubler structure consisting of an HSMS-

5   2702 Schottky diode pair and a load capacitor as shown in Fig. 4. To avoid high impedance
and the capacitive coupling of AC current in long parallel lines, there were two rectifier
configurations for the each pair of coils on the opposite sides of the tire. The DC output
voltages of the two rectifier pairs were summed by connecting the middle taps of two coils
on the same halves of the tire, as shown in Figs. 3 and 4. During the tests the power

10   consumption of the readout and RF transmission electronics were simulated with a R = 500Ω
resistor. The goal was to obtain the power of 100mW for this resistor. This would mean that
a voltage of 7.1 V over R.

The communication from the tire electronics to the reader equipment in the car body is

15   implemented by changing the load resistance of the rectifier circuit. This is done using
transistor T1 and resistor R2. Changing the gate voltage of the transistor changes the
effective DC load of the rectifier and this can be detected by the reading equipment in the car
body via the changed mutual inductance between the transmitter and the receiver coils. The
change of the mutual inductance between the coils changes also the impedance of the

20   transmitter coil.

The idea of this coil configuration is to provide power at a single position inside the tire
independent of rotation angle of the tire. Imagine, for example, that coil3 (L3) is energized
with magnetic field. The dc current produced by rectifier D5/D8 flows to load resistor R via

25   L3, L1 and back via L2 and L4. A corresponding dc path is found for every coil.

Fig. 4. shows a circuit of the voltage rectifiers, four tuned receiving coils connected to load
resistor R and the device for communication consisting of transistor T1 and resistor R2.

Component	Value
C1	440pF
C2	450pF
C3, C4	1μF
C5	350pF
C6	330pF
R	500Ω

Table 4. Component values of the circuit on figure 4 at the frequency of 6.78MHz.

4. Tests and results

4.1   Transmitted power

The output transistors turned Q2 and Q3 of Fig. 2 turned out to be too slow for frequencies higher than 6.8 MHz. Therefore the tests were performed at only one frequency. First the exact resonance frequency was found out. This proved to be 6.48 MHz; in other words, slightly less than the official band 6.765-6.795 MHz. Because the exact frequency is irrelevant, no adjustment of resonance frequency was tried and the results shown here are for 6.48 MHz.

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The tire in the experiments is Nokian Tyres Hakkapeliitta 2 (195/65 R15). The table 5 shows how much power we were able to get inside the tire for different feed coil distances from the tire surface. The feed coil was tangential to the surface of the tire, see Fig. 11. The tire was

Distance from the tir (cm)	Minimum voltage (V)	Maximum voltage (V)	Minimum power (mW)	Maximum power (mW)
0	12.0	15.7	288	493
5	10.8	13.1	233	343
7.5	8.1	9.4	131	177
10	6.2	7.2	76.9	104
12.5	4.9	5.9	48.0	69.6
15	3.9	4.4	30.4	38.7
20	2.5	2.8	12.5	15.7

installed to the rim. Minimum and maximum values are given because the induced voltage
5   drops when the feed coil is between receiving coils.

Table 5. The amount of rectified power given to a 500 Ω resistor inside the tire for different distances between feed coil and tire surface. Frequency is 6.48MHz. In this experiment only coil 4 is energized.

10   It should be pointed out, that higher power levels could be achieved if faster power transistors can be found (2SA1258/2SA1259 and 2SC3144/2SC3145, for example).

4.2   Current in the feed coil

From formulas [1] and [3] we obtain the current running through the feed coil by measuring
15   the voltage induced into a test coil. If the area of the loop A is small, we can assume that the density of the magnetic field H generated by the feed coil is constant across this area. We

place the test coil in the center of the feed coil. The induced voltage in the test loop generated by the current i in the feed coil is

$$U_{RMS} = \mu_0 \omega A_t N_t \frac{N\,i}{\pi\sqrt{a^2 + b^2}} \left(\frac{a}{b} + \frac{b}{a} \right),$$ [11]

where μ_0 the permeability of air, N_t is the number of turns in the test coil, A_t is the area of the

5   test coil, N is the number of turns of the feed coil, and a and b are the side lengths of the

rectangular feed coil. By using a test coil ($A_t = 18.1 \cdot 10^{-4} m^2$, N = 4) the rms current in the

feed coil was measured and found to be about 2A. Thus there is still a large margin with the

absolute maximum allowed 11.23 A. The resistance of the feed coil at 6.48 MHz is about 1Ω.

Therefore the power consumed in the feed coil $P = RI^2 = 4$ W. The overall power

10   consumption of the supply electronics P_{total}=16.9 W. Thus the efficiency of the circuit is η =

24 %.

4.3   Band width and Quality factor

The quality factor of the resonating system is obtained with the following formula

$$Q = \frac{f_r}{f_{-3dB,h} - f_{-3dB,l}},$$ [12]

15   where f_r is the resonance frequency and $f_{-3dB,h}$ and $f_{-3dB,l}$ are the frequencies at which the

transmitted power has been halved. In test setup the feed coil was installed 11 cm away from

the surface of the tire, see Fig. 12. The frequency of the signal generator was swept over the

resonant frequency of the system and the power in the 500-Ohm load resistor in the tire was

recorded. From figure 5 we get values f_r=6.49MHz, $f_{-3dB,h}$ and $f_{-3dB,l}$ =6.60MHz-

20   6.39MHz=0.21MHz and thus the quality factor is $Q \approx 31$.

Fig 5 is a graph showing the power in the 500Ω resistor versus frequency at the distance of

11cm. $(Q \approx 31)$

4.4   Effects to the tuning caused by external loads.

Various measurements were done in order to find out the influence of different objects close to the feed coil to the tuning. In the first tests no other objects where included, though, but the coil was brought in near contact to the tire (2cm away from the outer surface). As can be seen from figure 6, the resonance frequency does change significantly from the value, when the test tire was 11cm from the feed coil. The quality factor, instead, is reduced to $Q \approx 22$.

Figure 6 is a graph showing the power in the 500Ω resistor versus frequency at the distance of 2 cm. ($Q \approx 22$).

Figure 7 is a graph showing the power in the 500Ω resistor versus frequency at the distance of 11cm. An aluminium block was installed 5cm behind the feed coil.($Q \approx 30$).

In the second set of tests, aluminium (450 x 156 x 28 mm^3) and iron (187 x 144 x 106 mm^3) blocks were brought to the distance of 5cm from the feed coil. The feed coil remained at the distance of 11 cm from the tire and the metal blocks were installed behind the coil. Curves in figures 7 and 8 show quite a remarkable change in the resonance frequency. The quality factor is reduced as well as the power transmitted into the load resistor.

Figure 8 is a graph showing the power in the 500Ω resistor versus frequency at the distance of 11cm. An iron block was installed 5cm behind the feed coil. ($Q \approx 28$).

Figure 9 is a graph showing the power in the 500Ω resistor versus frequency at the distance of 17cm. An empty bucket was installed between the coil and the test tire. ($Q \approx 33$).

In the third set of tests an effect of water was measured. First an empty bucket was installed between the feed coil and the test tire to give reference values. Now the feed coil was 17cm from the tire. After this the bucket was filled with water and the power versus frequency graph was measured once again.

Figure 10 shows the power in the 500Ω resistor versus frequency at the distance of 17cm. An Bucket full of water was installed between the coil and the test tire. ($Q \approx 33$).

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In conclusion of these measurements, the resonant frequency is sufficiently insensitive to the coil position with respect to the tire. Also the band width of the power transmission remains high, at least 200 kHz. These results mean that no real-time tuning of the feed coil is needed. This would have been a difficult task because of the high voltage over the feed coil. In these

5   tests the rms voltage was about 180 V. Also the resonance is not sensitive to the presence of water between the feed coil and tire. On the other hand, large metal parts close to the feed coil affect the resonant frequency. So the metallic environment of the feed coil should remain unchanged, and the presence of large metallic parts near the feed coil should be taken into account in the design of the coil. If the feed coil can be placed very close to the tire (2 cm),

10   large power can be transferred - even 0.38 W in these experiments.

Figure 11 shows a graph which presents the power in the 500Ω resistor versus turn angle of the wheel at the distance of 11 cm.

Figure 12 shows a graph which presents transmitted power versus frequency is being

15   measured. The coil is at a distance of 11cm from the surface of the tire.

Figure 13 shows a test setup is installed to measure the effect of an aluminium block to the transmitted power.

Figure 14 shows a test setup is installed to measure the effect of a bucket full of water to the inducted power.

20   Figure 15 shows a feed coil and amplifier.

Figure 16 shows receive coils in tyre and feed coil in the wing.

Figure 17 shows an alternative position of the feed coil. This position, shown for front wheel, ensures that the distance between feed coil and receiver coil does not vary.

According to figure 18 the diodes D of the circuit are grouped as rectifiers 31-34 and rectfiers are grouped in pairs 31-32 and 33-34 as rectifier groups 30.